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The Measurement of Skin Friction in Supersonic Flow by means of Heated Thin Film Gauges

By B. J. Bellhouse and D. L. Schultz

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Summary.

The application of heated thin film gauges to the measurement of mean skin friction in compressible flow is described. It is shown that the calibration of the gauges is independent of Mach number, at least up to $M = 3$, provided the fluid properties are calculated at the appropriate film temperature. The gauges are calibrated by reference to surface tubes and also by comparison with the theoretical solution of Spalding and Chi.

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*Replaces University of Oxford Dept. of Eng. Science Report No. 1002—A.R.C. 27402.

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1. *Introduction.*

The heated elements used to measure skin friction consisted of a platinum film painted and then baked onto a pyrex glass substrate. The films have a temperature coefficient of about $2{\cdot}5 \times 10^{-3}$/ deg C and one use of the film is as a resistance thermometer. If the film is heated electrically, the heat transfer rate from the hot film is related to the mass flow-rate of the air near the film surface.

In incompressible flow the equation

$$Nu \equiv \frac{q_w L}{k_w \Delta T} \alpha \left(\frac{\rho \tau_w}{\mu^2}\right) \sigma^{1/3} L^{2/3} \tag{1}$$

has been derived in Refs 1 and 2, and supported experimentally in the form $\frac{q_w L}{\Delta T} \alpha \tau^{1/3}$ to a high degree of accuracy for both laminar and turbulent boundary layers, although the calibrations may differ by a constant factor.

Equation (1) may be written

$$\frac{q_w L}{\Delta T} \alpha\, \tau_w{}^{1/3}\, C_p\, \sigma^{-2/3} (\varrho\mu)_w{}^{1/3} \tag{2}$$

Since C_p and σ may be taken constant across the thermal boundary layer produced by the hot element, the effect of compressibility is confined to the factor $(\varrho\mu)^{1/3}$. In Ref 1 this effect is shown to be negligible. This fact may easily be checked, for if the temperature ranges from 0 deg C to 100 deg C across the thermal boundary layer, then

$$\frac{(\varrho\mu)^{1/3}{}_{T = 0°C}}{(\varrho\mu)^{1/3}{}_{T = 100°C}} = 1{\cdot}02$$

(The pressure is assumed to be constant across the thermal boundary layer and the equation of state and Sutherland's viscosity law are used.) The mean value of $(\varrho\mu)^{1/3}$ will be even closer to the wall value $(\varrho\mu)_w^{1/3}$

Equation (1) has also been derived in Ref 3 by means of a detailed mathematical method, which establishes that the Mach number does not appear as an additional parameter; for although the compressible temperature distribution in the sublayer has an additional term (a function of stream Mach Number), this term does not contribute to heat transfer.

In a continuous-running tunnel, the right-hand side of equation (2) will depend on probe-temperature and the pressure at the probe position. For a given probe temperature, equation (2) reduces to

$$\frac{q_w L}{\Delta T} \alpha\, (\rho\tau)_w^{1/3} \tag{3}$$

The sensitivity of the instrument depends on the value of

$$\frac{\partial\left(\dfrac{q_w L}{\Delta T}\right)}{\partial(\rho\tau)_w} \propto \frac{1}{(\rho\tau)_w^{2/3}}$$

which is greatest when the product $(\rho\tau)_w$ is smallest. This may be achieved at low speeds or low densities, exactly when a conventional surface tube is at its least sensitive. Sensitivity also depends on the temperature difference ΔT. The difference between the probe temperature and the adiabatic wall temperature may be increased by operating the probe at a higher temperature. Reduction in sensitivity at high values of $(\rho\tau)_w$ presents no difficulties, and it is simplest first to develop the hot element probe in the types of flow where other instrument and theory are adequate, and then study low speed or low-density flows at a later stage. One advantage which the instrument has over floating element balances and surface tubes is its high frequency response. It is possible to make fluctuating skin friction measurements at frequencies as high as 10 kc/s although calibration is necessary, and is difficult above 1 kc/s.

The work described in this report was completed in two wind tunnels at the National Physical Laboratory, Teddington. In the 9 inch x 3 inch working section induced-flow tunnel, only subsonic measurements were taken. A probe was mounted on the tunnel wall, and since the stagnation pressure could not be altered from near-atmospheric, it was not possible to vary Mach number and Reynolds number independently. However, a range of values of $(\rho\tau)_w$ was achieved by varying the Mach number from 0·22 to 0·835.

The 2·6 inch x 1·5 inch blowdown tunnel at the N.P.L. was capable of running at $M = 1$ and $M = 3$ for a wide range of stagnation pressures, and so this tunnel has been used for the bulk of the skin friction measurements.

During the early experiments in the 9 inch x 3 inch tunnel, it was discovered that the probes used in low speed flow were burning out. This was found to be due to local hot-spots due to uneven painting, and if five coats of paint were applied (firing between each coat) instead of a single coat, the probes could be heated to about 620 deg C, the annealing point of the substrate. Since the sensitivity of the instrument depends upon the temperature difference between the probe and the wall, it is possible to improve the sensitivity by running the probe at a high temperature. This was unnecessary in the blowdown tunnel, where temperature differences of 50 deg C were quite sufficient. However multi-coating makes the film virtually indestructible, and this is a significant improvement on the films made previously with one or two coats of platinum paint.

2. *The Experiments.*

For measurements of skin friction at high subsonic speeds the 9 inch x 3 inch induced flow tunnel at N.P.L. was used. A 10 inch diameter disc was fitted in the side walls of the tunnel and in this disc were located the heated thin film element, a second unheated thin film for surface temperature measurement, a static pressure hole and a razor blade surface tube (Ref. 4). Parallel-wall subsonic liners were used and the Mach number and Reynolds number were varied in order to obtain a range of values of $(\rho\tau)_w$. A sketch of the hot element probe is shown in Fig. 1a. In Ref. 4 it is shown that for a Mach number between 1·8 and 2·7 the calibration of the razor-blade surface tube is independent of Mach number, but is distinct from the subsonic calibration, such as that obtained in Ref. 5. If the calibration of Ref. 5 is used, then for $M > 0{\cdot}73$ the points fall away from the straight line (Fig. 2a), but if use is made of the calibration of Ref. 6, then the higher Mach number points fall on the straight line as in Fig. 2b.

The results shown in Fig. 2b suggest that the law $\dfrac{q_w L}{\Delta T} \propto (\rho\tau)_w^{1/3}$ has the correct exponent, and is independent of Mach number up to $M = 0{\cdot}835$. In order to extend these results to higher Mach numbers, the 2·6 inch x 1·5 inch blowdown tunnel at N.P.L. was recommissioned, and a photograph of the flat-plate model used for the experiments is shown in Fig. 1b. The two chief advantages of the blowdown tunnel were its large range of stagnation pressures, permitting a range of Reynolds numbers for a given Mach number, and its range of Mach numbers for which it is designed to run ($M = 1$, 1·5, 2, 3 and 4).

No attempt was made to fix transition at the leading edge of the flat-plate model. Measurements of skin friction with a heated element and with a razor-blade surface tube were made for a range of Reynolds numbers at $M = 1$ and $M = 3$, and the results are contained in Fig. 3. The surface tube calibration given in Ref. 4, uncorrected for Mach number effects, was used. Although one line is drawn through all the points, it does appear that the calibrations at $M = 1$ and $M = 3$ are distinct. To see if this was the fault of the surface tube or the hot element, a calculation of the skin friction by the method of Spalding and Chi, Ref. 7, was embarked upon. It was assumed that the boundary layer was turbulent from the leading edge; but it should be noted that this assumption is incorrect at low Reynolds numbers. The results shown in Fig. 4 show that once the transition point has moved close to the leading edge, the calibration for $M = 1$ and $M = 3$ is unique and linear, and of the form $\frac{i^2R}{\Delta T} = A\left[\frac{k_w}{\mu_w{}^{2/3}}\sigma^{1/3}L^{2/3}\,(\rho\tau)_w^{1/3}\right] + \left[B\right]$

Unfortunately the strip of 15 hot element gauges was placed too far away from the leading edge to identify the transition point, and oil film techniques are probably not sufficiently accurate. It would have been possible to trip the boundary layer, but in view of the large range of Reynolds numbers used, great care would have been necessary to avoid unwanted effects of local separation.

3. *Further Work.*

In low speed flow it is a simple matter to distinguish between laminar and turbulent boundary layers, merely by looking at the probe output on an oscilloscope. The problem of location of transition, stagnation and separation points and shock wave position in supersonic flow, will be investigated in a future series of experiments.

4. *Conclusion.*

The calibration equation for a thin film heated element has been shown to be

$$\frac{i^2R}{\Delta T} = Ak_w\left(\frac{\rho\tau}{\mu^2}\right)_w^{1/3} \sigma^{1/3}L^{2/3} + B\,,$$

where all fluid quantities are evaluated at the probe temperature. For a given probe, running at a fixed temperature, in a given fluid, the calibration reduces to

$$\frac{i^2R}{\Delta T} = A^1\,(\rho\tau)_w^{1/3} + B^1$$

A, A^1, B, B^1, are constants.

The calibration is independent of Mach number up to $M = 3$.

5. *Acknowledgements.*

Discussions with Dr. J. Nash and Mr. K. Winter have proved most helpful. Mr. F. H. Bellhouse helped with the experiments, and made the probes. The work described in this report is part of a programme supported by the Aerodynamics Division, National Physical Laboratory.

LIST OF SYMBOLS

τ_w	Wall shear stress, or skin friction.
ϱ	Density of air
μ	Viscosity of air
σ	Prandtl number
L	Length of element in stream direction
k	Thermal conductivity of air
q	Heat transfer rate per unit time per unit area
T	Temperature
ΔT	Temperature difference between probe and neighbouring wall
Nu	Nusselt number $\equiv \dfrac{q_w L}{k_w \Delta T}$
C_p	Specific heat of air
i	Film current
R	Film resistance
M	Mach number
Re	Reynolds number
A, A^1, B, B^1	Constants
suffix w	Value of quantity at the probe surface

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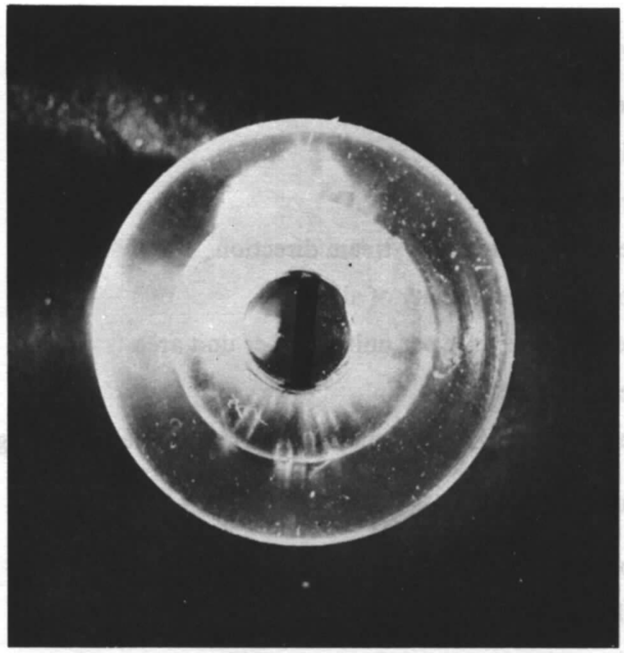
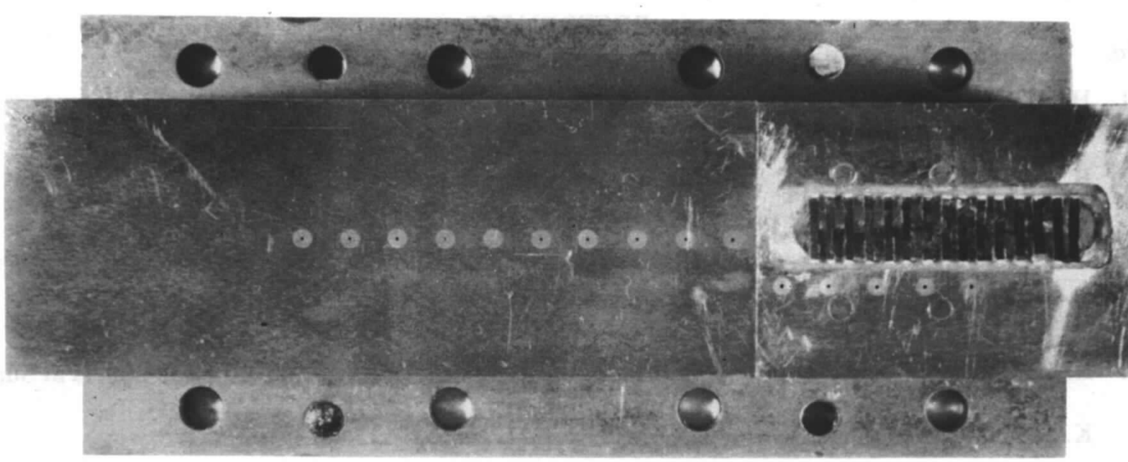


(a) 0·25 INCH

FIG. 1a. Thin film element for use on tunnel wall.



0 1 2
(b) INCHES

FIG. 1b. Thin film elements mounted in a flat plate.

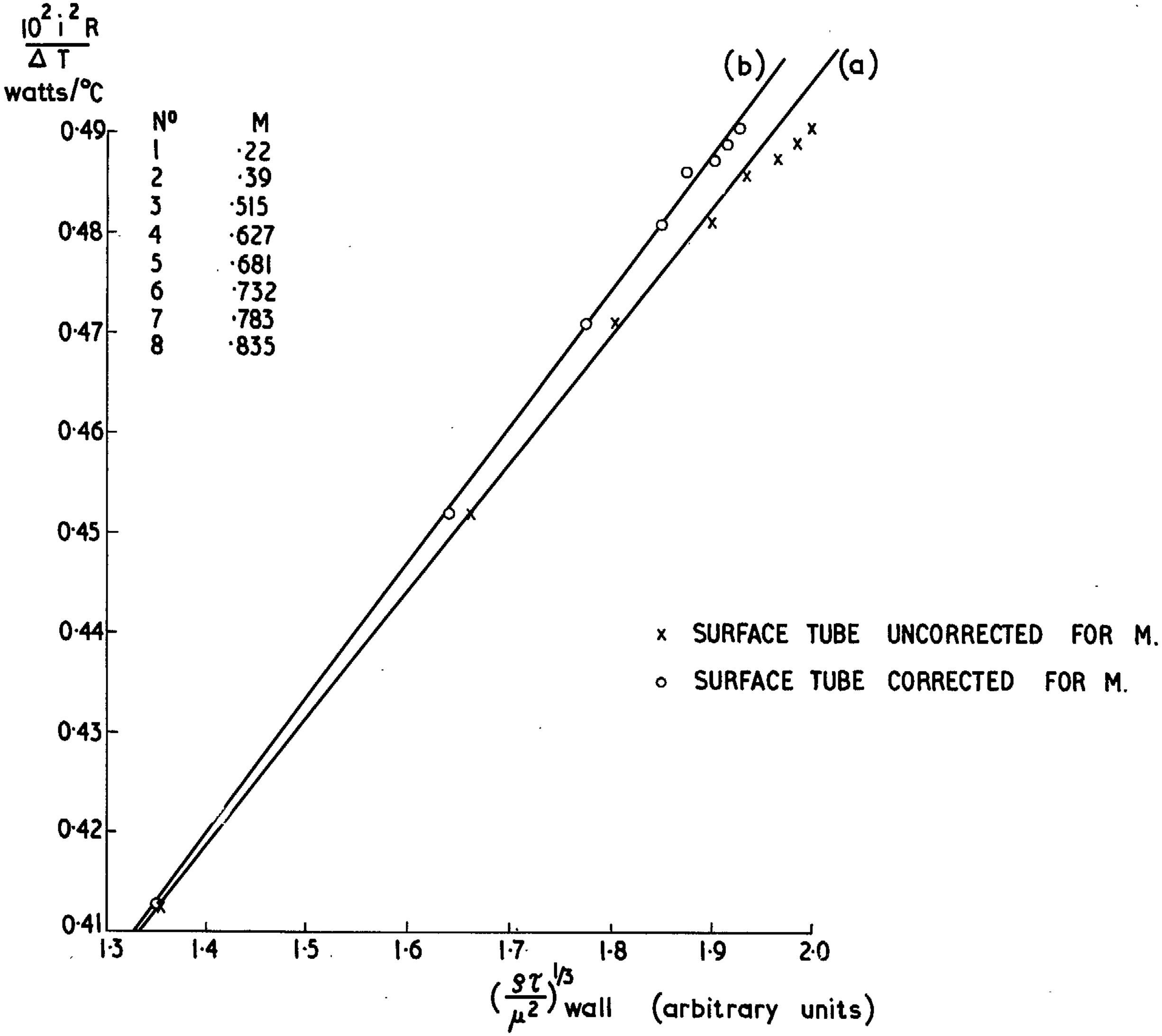


FIG. 2. Skin friction measured with a heated element, compared with a surface tube.

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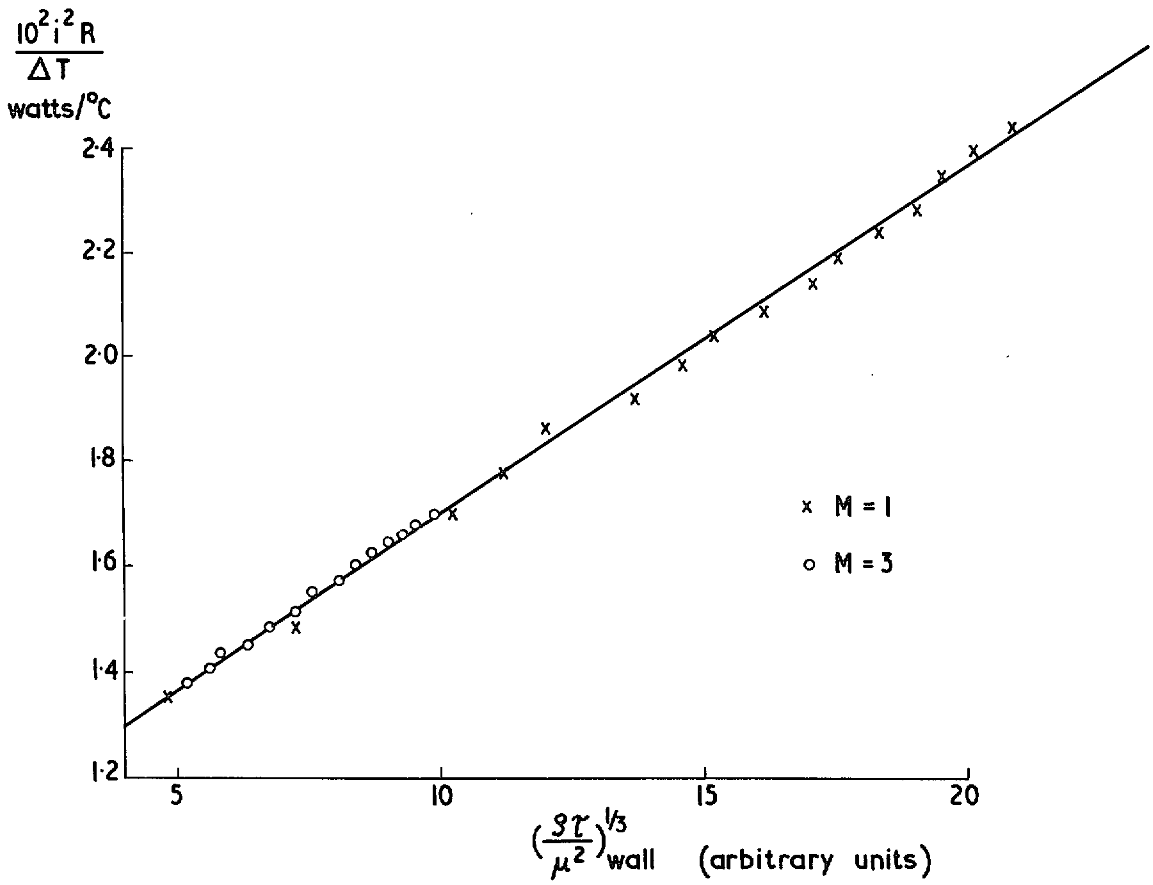

FIG 3. Skin friction measured with a heated element, compared with a surface tube.

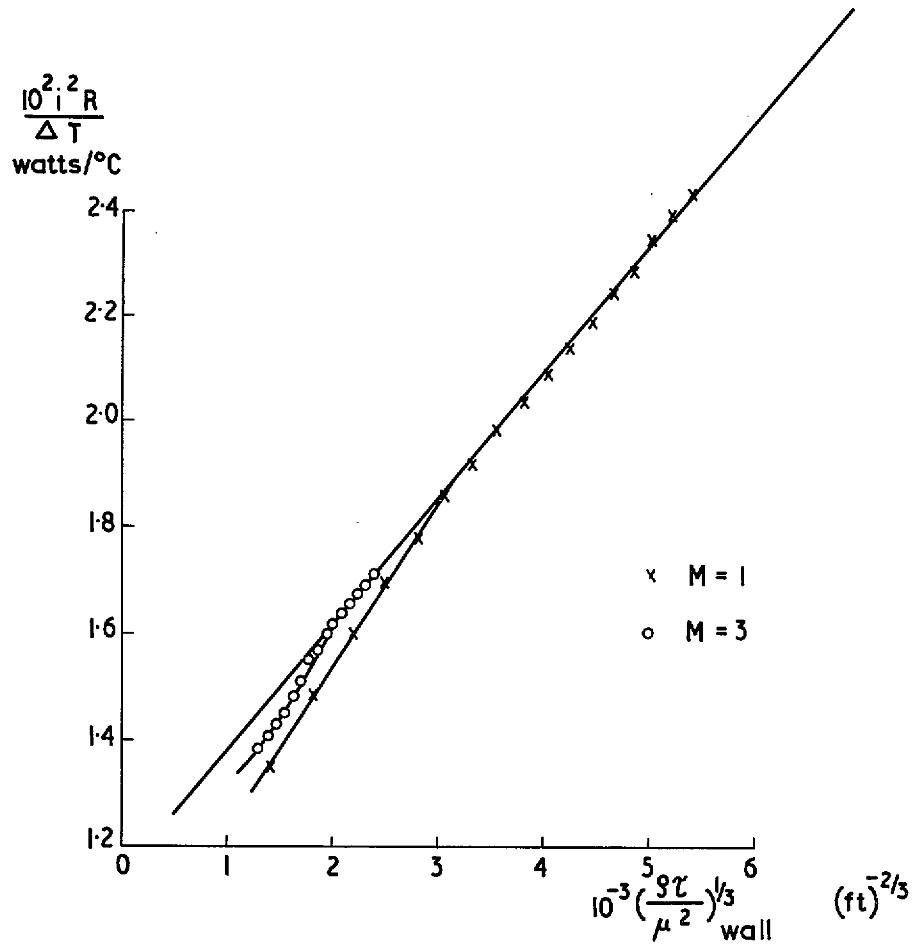

FIG. 4. Skin friction measured by a heated element compared with a theoretical solution of a turbulent boundary layer.

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